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Dune-slope activity due to frost and wind throughout the north polar erg, Mars

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Abstract

Repeat, high-resolution imaging of dunes within the Martian north polar erg have shown that these dune slopes are very active, with alcoves forming along the dune brink each Mars year. In some areas, a few hundred cubic metres of downslope sand movement have been observed, sometimes moving the dune brink ‘backwards’. Based on morphological and activity-timing similarities of these north polar features to southern dune gullies, identifying the processes forming these features is likely to have relevance for understanding the general evolution/modification of dune gullies. To determine alcove-formation model constraints, we have surveyed seven dune fields, each over 1–4 Mars winters. Consistent with earlier reports, we found that alcove-formation activity occurs during the autumn–winter seasons, before or while the stable seasonal frost layer is deposited. We propose a new model in which alcove formation occurs during the autumn, and springtime sublimation activity then enhances the feature. Summertime winds blow sand into the new alcoves, erasing small alcoves over a few Mars years. Based on the observed rate of alcove erasure, we estimated the effective aeolian sand transport flux. From this, we proposed that alcove formation may account for 2–20% of the total sand movement within these dune fields.

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Supplementary material: A full listing of the HiRISE images used within this study and supplementary images, and analysis descriptions are available at https://doi.org/10.6084/m9.figshare.c.3936919

Background

The Martian north polar erg contains 844 000 km^2 of medium- to large-sized dark dunes (Hayward 2011). About 25% of this areal extent is covered in densely packed fields of barchanoid ridges and transverse dunes. The remainder contains less-dense dune fields (*c.* 65%) and isolated barchans. These dunes appear to be composed of dark, granular material eroding from the basal unit of the north polar layered deposits (NPLD) (Tsoar *et al.* 1979), which may be remnants of an ancient erg that predates the polar cap (Byrne & Murray 2002; Fishbaugh & Head 2005; Tanaka *et al.* 2008; Massé *et al.* 2012). As with all landforms within the polar region, these dunes are covered with seasonal frost primarily composed of CO_2 (Leighton & Murray 1966) starting in early autumn (Kelly *et al.* 2006). The frost layer accumulates and densifies (Kelly *et al.* 2006; Matsuo & Heki 2009) through the winter, until it begins to sublimate in early spring (Kelly *et al.* 2006). The seasonal ice layer is generally gone by the end of spring, although patches may linger in small protected cold traps (Hansen *et al.* 2013).

Within the current Martian north polar erg, numerous mass-wasting alcove–apron features are found on many of the dunes' lee (i.e. downwind) slopes (Figs 1 & 2). Alcoves (the erosional upper triangle) originate at the brink of the dunes (i.e. the top edge of the slip face) and usually feed into an apron (the depositional lower triangle) that may extend partially or fully down the slope, or even beyond the dune's lee margin. We note that in rare cases, the alcove and apron are connected by a channel (see the subsection on 'Some intriguing local-scale variations' later in this paper) – similar in appearance to dune gullies within the southern mid-latitude dune fields, but the channel formations are rare and it is not yet clear why channels sometimes form – thus, channel formation will not be specifically discussed within this study. Additionally, as the definitive portion of a gully is its channel, we generally refer to these north polar dune mass-wasting features as 'alcoves' or 'alcove–apron' (AA) features, and not 'gullies'. However, these alcove–aprons do otherwise share morphological and, as will be discussed, activity-timing similarities with the southern mid-latitude dune gullies (e.g. Diniega *et al.* 2010; Dundas *et al.* 2010, 2012, 2015). Thus, it seems likely that identifying the processes forming these north polar features will provide useful environmental context and process information relevant to understanding the evolution and modification of Martian dune gullies. (However, genetic connections between features is not specifically explored within this study.)

The active formation of alcove–apron features were first reported on by Hansen *et al.* (2011), who noted that these features formed annually and were extensive (i.e. fresh-appearing alcoves were found on *c.* 40% of the dunes sampled within Kolhar dune field; the field names are informal but are generally consistent between studies of these sites). Kolhar dune field was surveyed within images taken during Mars years (MY) 29 and 30, and similar types of activities were also noted within Tleilax and Buzzel dune fields, during the same time frame. As per convention, the solar longitude (L_S) range of 0°–360° defines a Mars year/one orbit of Mars about the Sun, and seasons are defined as: northern spring, L_S 0°–90°; summer, L_S 90°–180°; autumn, L_S 180°–270°; winter, L_S 270°–360°. The start of the Mars calendar (i.e. L_S 0° MY 01) is on 11 April 1955 (see Piqueux *et al.* 2015 for a complete description). Furthermore, it was noticed that the alcove–aprons were correlated with springtime sublimation activities (e.g. the appearance of dark spots and flows – such as those described within Gardin *et al.* 2010) and even an apparent in-process dust/sand avalanche has been observed over one of the alcoves (Hansen *et al.* 2011). This led to an initial hypothesis that these features were formed through a seasonal frost-driven process – and, specifically, that springtime sublimation was leading to the alcove-formation activity (Hansen *et al.* 2011).

A second study (Horgan & Bell 2012) focused on the Kolhar dune field noted that some new alcoves were first observed under the winter frost, thus implying a formation early enough for frost to form over the alcove as autumn/winter proceeded, and possibly completely preceding frost deposition. This led to the hypothesis that wind-driven processes may play a dominant role (Horgan & Bell 2012), causing alcove formation during defrosted portions of the year, including the mid–late summer. Wind-controlled gully activity had also previously been hypothesized for crater-wall gullies within the southern mid-latitudes – in controlling the locations of mobilizable granular deposits and/or in initialization of the mass wasting (Treiman 2003, 2008).

A third study (Hansen *et al.* 2015), which considered four dune fields and examined activity within each during MY 30 and 31, confirmed that some alcoves were first visible under the frost, but showed that formation of the new alcoves was likely to be limited to autumn and winter. In this and all studies of these features, timing of the alcove-formation activity generally cannot be constrained more narrowly due to a lack of images taken during those seasons (in autumn, light levels are too low and/or the polar hood is too opaque; and in winter, the region is in polar night). Additionally, this third study confirmed that apron-forming activity was sometimes seen in the spring, as the frost layer sublimated. These implicated frost-driven processes, although possibly coupled with wind-based controls.

With our study, we aimed to more rigorously evaluate these different formation hypotheses. This study greatly extended the work started by prior surveys by encompassing seven dune fields and spanning up to 4 Mars years within each field. Additionally, as will be discussed, we considered a wider range of measurements and variables in evaluation of the different alcove–apron-formation process hypotheses. These extensions proved vital as we found agreement with observation results from all of the previous studies – alcoves do often first appear under the frost (as observed by Horgan & Bell 2012) (Fig. 2), but alcove formation is seasonally constrained to the autumn/winter (as observed by Hansen *et al.* 2011, 2015) and further enhancement is correlated with springtime frost sublimation (Hansen *et al.* 2015) (Figs 1 & 2).

Within this study, we also monitored the erasure of the alcove–apron features, or equivalently the restoration of the dune slopes (Fig. 3). Despite the prolific alcove–apron activity, dune brinks within most of the north polar erg appear sharp and clean, and dune slopes remain mostly unscarred. This implies that these dunes are ‘restored’, most probably through the aeolian processes that commonly build and maintain dune forms (Bridges *et al.* 2013).

Martian dune aeolian activity has been observed within the north polar erg. Bourke *et al.* (2008) observed the gradual deflation of several small (*c.* 1000 m^2) dome dunes over a 5 year time span (1999–2004) in Mars Global Surveyor's Mars Orbiter Camera (MOC) data. More recent global studies of Martian bedforms using higher-resolution data have found that dunes and ripples are migrating across the planet, and, in particular, within the north polar erg (Bridges *et al.* 2011, 2013; Banks *et al.* 2014, 2015). For example, Bridges *et al.* (2013) documented five sites where dome or small barchan dunes were migrating at relatively high rates. Over both small sand patches and larger dunes, ripple movement has been noted to be widespread on polar dunes (Bridges *et al.* 2013; Banks *et al.* 2015; Middlebrook 2015), including ripple formation in newly formed small alcoves (Hansen *et al.* 2011).

Such results have been somewhat surprising as sand mobility may be subdued in the polar regions when the dune surface is covered in frost and thus no longer in contact with the wind (as discussed in Bridges *et al.* 2013). The dune surfaces may also become seasonally indurated as frost collects within the pore space (e.g. Bourke *et al.* 2009) and it has been hypothesized that the interior of the dunes could be perpetually cemented/frozen (e.g. Bourke *et al.* 2008; Feldman *et al.* 2008), immobilizing the majority of the sand. Theoretical studies of the seasonal thermal environment and diffusive exchange between the atmosphere and sand have shown that the sand may become indurated on daily and seasonal timescales due to the formation of pore ice within a surficial layer (Kreslavsky 2010), and neutron flux and thermal inertia measurements support the idea of an ice-rich core with a dry surface layer (Feldman *et al.* 2008; Putzig *et al.* 2013). Additionally, the arcuate ridges/remnant layers visible in some north polar dunes may provide geomorphological evidence of some level of cohesion of the sand (Schatz *et al.* 2006; Horgan *et al.* 2010). Ground ice and surface induration are also thought to cause the subdued dune morphologies and lack of orbital detections of bedform movement in the south polar regions (Fenton & Hayward 2010; Banks *et al.* 2016).

In summary, observations of the north polar dunes to date indicate that both aeolian and seasonal (frost-related) processes play a role in the evolution of these dunes, and that both types of processes should be considered in the interpretation of the geomorphology and surface changes of the north polar erg. However, the relative proportions of sand transport due to aeolian v. seasonal polar processes had yet to be quantified. Our study aimed to do this: we first outline our study sites and our methodology for identifying and measuring changes/features in the section on Methodology. In the section on 'Observed alcove activity', we discuss our measurements – where and when alcove–apron features form and how long they take to be erased. We then discuss these results in the Discussion – implications of our observations for different formation hypotheses and our estimations of dune-slope activity through each of alcove–apron activity and wind-driven sand transport.

We note that in examining changes over multiple locations and multiple Mars years, we have considered all observations both individually and in-aggregate, and from this we have begun to separate general changes, feature characteristics and processes from those that appear site-, dune- or year-specific. Within this paper, we focus on broad results, and thus we mainly present only aggregated or averaged measurements and 'representative' examples. We generally present only study sites and years where the full survey and measurements have been completed; observations from a few additional Mars years where the measurements are not yet complete are referenced in this paper, and we emphasize that all collected data are consistent with what is presented here. We briefly discuss a few interesting variations (see the subsection on ‘Some intriguing local-scale variations’ later in this paper), as well as questions about how to reconcile different proxy observations of the dune interior (see the subsection on ‘A comment on the interior of polar dunes’), but leave development of a more complete understanding of how to incorporate these items into the full alcove-formation model for future work.

Methodology

Selection of study sites

Our seven study sites were chosen as they span a range of local topography, dune type and distance from the source material (the NPLD) (Fig. 4), and because they contain numerous overlapping images spanning at least 2 Mars years. Site inspection in some cases did not cover all available HiRISE images – we report here on all fields and years where identification of new alcoves, their measurements and their formation timing has been completed for the full study site, to date. As previously mentioned, we also report on some examples from Mars years where we have not completed the full survey and alcove measurements. (A full listing of the HiRISE images considered for our completed surveys are given in the Supplementary material – although note that the overlap was not perfect, so some portions of the dune field study site were not visible in all HiRISE images.)

Change detection

By comparing pairs of high-resolution images taken by the High-Resolution Imaging Spectrometer Experiment (HiRISE) (McEwen *et al.* 2007) on the Mars Reconnaissance Orbiter (MRO), it is possible to identify and constrain when the alcoves form or disappear. This methodology has been used for many Martian change-detection studies, including those focused on gully (alcove–channel–apron (ACA)) formation within the southern mid-latitudes (e.g. Diniega *et al.* 2010; Dundas *et al.* 2010, 2012, 2015) and for aeolian bedforms (e.g. Bridges *et al.* 2011; Chojnacki *et al.* 2015). However, two factors complicate this investigation within the north polar dunes:

- During the northern autumn and winter (*c.* L_S 165°–355°), HiRISE usually does not image the north polar region as a polar hood forms (starting at *c.* L_S 150°–165°: Benson *et al.* 2011) and the Sun drops in the sky, yielding hazy, and then too-dark and too-low signal-to-noise ratio (SNR) images.
- When HiRISE does image frost-covered dunes, the layer of frost can obscure or enhance topography that was not visible (but present) when the dune was defrosted. This makes identification of changes difficult when comparing a frost-covered image with a defrosted image (Hansen *et al.* 2015).

Due to the second complicating factor, we have identified new alcoves only via comparison of well-illuminated, frost-free images (*c.* L_S 90°–135°), taken approximately 1 Mars year apart and thus under similar illumination conditions. After a change was identified within the frost-free images, a careful comparison of all intervening images was done to identify when the alcove first appears. We understand that this will yield a lower-bound on rates of activity – as, potentially, a small alcove could form and be mostly erased some time between the two images used in the initial, frost-free comparison. However, as it appears that it takes at least a few years for most alcoves to disappear (as discussed below), we are reasonably confident that our estimates of activity rates are representative.

As will be discussed, the first clear sign that a change had occurred was usually within the first image taken following polar night, which generally was an image of a frosted dune. In these cases, the only evidence that we considered conclusive enough were changes in the dune brink's shape (Fig. 2) as alterations in shadowing due to the addition of frost and illumination changes can make it difficult to tell if the topography of the dune slope has changed. From this, we bracketed the formation timing for the alcove – although, due to the first complicating factor, generally much more loosely than was possible for dune-gully activity within the southern mid-latitudes (e.g. Dundas *et al.* 2012).

We did find one example of a much tighter bound on the timing of alcove formation. For our study, we have been actively targeting more images during very late summer or late winter to narrow the image gap as much as possible and, in particular, to check for late summer/early autumn alcove formation. Due to the formation of the polar hood, nearly all of the few images from this time frame are so hazy that alcoves and other features on the dunes are not clearly visible. To date, we have found only one image that is sufficiently clear for identification of the appearance of a new alcove by early autumn (Fig. 5). This identification was also enabled by the size of the new alcove (*c.* 20 m wide and 20 m long: Fig. 5f) that matches both size and shape with the dark triangle feature and slight dune brink deviation seen in the early autumn HiRISE image (taken at L_S 191° MY 32: Fig. 5e). Similar dark features on dunes' lee slopes throughout the early autumn image also appeared spatially correlated with small changes to the dune slope's texture and margins (visible when defrosted images taken at L_S 124° and L_S 169° MY 32 are compared with the image taken at L_S 126° MY 33), suggesting that many of these dark features (if not all of them) may be the dimly visible outlines of recent mass-wasting activity. Throughout this paper, we focus on our more confident identifications of activity and its timing – but this one example supports our proposed alcove-formation model (see the subsection on 'Evaluation of formation mechanism hypotheses' later in this paper), and will be a focus of future work.

After identifying when the alcove first forms, we tracked its evolution up to the feature's disappearance as the dune slope is restored (i.e. when the dune brink is re-straightened and the alcove is no longer apparent on the dune slope). In particular, we identified any further mass-wasting activity within the feature – which, as will be discussed, seems to be constrained to the spring season following the alcove's formation. By also identifying when the alcove has been erased, we then estimated the amount of sand needed for infilling, which we assumed was delivered primarily through wind-driven sand transport. We then compared this effective aeolian sand-flux estimate with the amount of sand being moved downslope (and downwind, based on the overall dune orientation) through alcove–apron activity, so as to estimate the relative significance of these two processes for the overall evolution of the Martian north polar dunes.

Additional measurements

As has been done in prior studies, we attempted to constrain the timing of when alcoves form as this can be a key piece of information for constraining the conditions under which the alcove activity occurs. However, since we lacked images during much of the Mars year (as discussed above), we also considered contextual information such as the orientation of the alcove with respect to the dune brink (Table 1) that, perhaps, could help us distinguish between different formation processes.

In addition to tracking where, when and how often alcoves formed, we estimated their sizes. New alcoves came in a range of sizes and triangular shapes. Within a site and a single Mars year, we found that length-to-width ratios of the alcoves could span from 0.1 to 4. In our identification of new alcoves, we restricted the new alcove widths to a minimum of 4 m (i.e. 2–3 times the lee-slope ripple wavelengths) so as to distinguish the slope changes from common dune avalanches and slumps, and to avoid uncertainty due to small shifts in shadows. Aside from this arbitrary lower-size cutoff, we found that most alcoves were 10–20 m in width (with some as wide as 60 m). Outside of the small alcoves that formed near the end of barchan horns, alcove lengths generally extended down 10–50% of the local dune lee-slope length (over very short slopes, such as barchan horns, the alcove may extend the full slope length), and composed 30–50% of the length of the full alcove–apron feature, when the apron was clearly defined.

Since the alcove aspect ratio varied so widely, we chose to focus on volume estimates for analysis and comparison of activity rates. Using HiRISE images of defrosted dune slopes with a low emission angle (to reduce foreshortening effects within images taken when the spacecraft is slewed – the emission angle is the angle between the instrument boresight and straight below the spacecraft, so an angle of zero means a nadir image and a large angle means an oblique view), we measured the planform-projected width and length of a new alcove (Fig. 6). We used these as approximate values of the ‘base’ and ‘height’ of the triangle (note that, to be conservative, we neglected the slope-angle factor, which would increase the ‘height’ of the triangle by 15% if the dune slope were originally at the angle of repose). Based on the relative dimensions of terrestrial dune dry avalanche features with similar morphologies (as explained in Hansen *et al.* 2015), we conservatively approximated the alcove depth as 1/100th of the alcove width. This approximation is rough, but did not appear inconsistent with our observations of the Martian features.

The resultant volume (=length × width^2/200) was then used to estimate the amount of sand moving over the dune slope – through both mass wasting (alcove formation) and aeolian sand flux (alcove erasure through infilling). By using the same volume estimates in quantifying the effects of both processes, the same estimation errors (e.g. due to using planform-projected measurements) should be present in both calculations and thus should factor out when we consider the relative impact of these two processes on dune evolution (see the subsection on ‘Relative importance of sand motion via frost or wind-driven processes for dune evolution’ later in this paper). We employed this ‘triangular prism’ approximation method because a digital terrain model (DTM) generated from a stereo-pair of HiRISE images (Kirk *et al.* 2008) does not exist for all of these fields and, in cases where one does exist, it was unlikely to include accurate representations of the small alcove features. In general, accurate DTM generation is difficult and complicated over the dark dunes (Mattson *et al.* 2012). Thus, while the DTMs can and have been used to look at, for example, the overall dune slope and dune form (e.g. Bridges *et al.* 2012; Atwood-Stone & McEwen 2013), it was less certain how well such a DTM would reproduce the original alcove shape and so we did not use them within this study.

Observed alcove activity

When the alcoves form

Except for our one autumn-formation observation (described above and shown in Fig. 5), throughout all fields the first appearance of an alcove was constrained to the time period between the last image taken during the summer (when, obviously, the dune was frost-free) and the first clear image taken following the polar night (usually when the dune was frost-covered) (Fig. 7; Table 2). In a few locations and Mars years, that first image was taken before sublimation activity has begun – in some of those cases, the new alcove may only have been visible as a slight (or, sometimes, large) deviation in the dune brink that was not present in the preceding frost-free image (Fig. 2). This implied that the alcove formed early enough for the frost to form over it, yielding three possibilities:

- The alcove formed on a completely frost-free dune, before any seasonal frost interacted with the dune surface (e.g. during summer).
- The alcove formed after a stable seasonal frost layer is deposited (i.e. during winter), but early enough for additional frost to form over the alcove, and thus for the slope, alcove and apron to appear uniformly coated.
- The alcove formed when seasonal frost (in some form) began to interact with the dune surface (i.e. during early autumn), but before a stable seasonal frost layer is deposited.

The first possibility was the basis of the proposal by Horgan & Bell (2012) that summer winds may initiate alcove formation. However, that hypothesis seems unlikely as we observed no alcove formation or enhancement during the imaged summer seasons (i.e. as late as L_S 166°: Fig. 6; Table 2), although we did see sand moving around and infilling preexisting alcoves during the summer. Thus, the lack of *any* observed alcove formation or enhancement activity during the imaged frost-free periods despite evidence of aeolian sand transport implied strongly that the activity is not summer-specific and is not caused by a frost-independent mechanism. Additionally, climate models have suggested that the strongest winds should occur at the edge of the polar vortex (as this area would experience the sharpest thermal gradients) (Forget *et al.* 1999; Richardson *et al.* 2007) – and thus that wind strength would be strongest in winter, then autumn, then spring and, finally, weakest in summer.

In considering the second possibility: we expect that a stable seasonal frost layer would shield the surface from the atmosphere and stabilize the underlying material. Such a layer would be likely to sinter into CO_2 ice as winter progresses (Kieffer *et al.* 2000; Kieffer 2007; Matsuo & Heki 2009) – the formation of CO_2 ice slabs over these dunes is supported by the appearance of cracks within the frost layer during spring (Fig. 8) (Portyankina *et al.* 2012). Additionally, in some locations, new furrows extending from the dune brink down the upwind slope (matched vertically with spots within the dune lee slope/aprons where sand has been removed) become visible when the frost has been removed (Fig. 8). These furrows appear reminiscent of 'spider'-like channels that form due to gas flow beneath a solid ice layer (Bourke & Cranford 2011; Diniega *et al.* 2013; Hansen *et al.* 2013). Although a full investigation of the formation process of these features is outside of our current study, this type of feature suggests that the seasonal frost layer over these dunes has solidified into an icy layer. No mechanism has yet been proposed for mass wasting to occur under such a frost layer, especially with some of the large alcove sizes (where would the sand go?) – so we find the second possibility unlikely.

Thus, we focus on the third possibility – that initial alcove-formation activity may occur during the autumn season, *before* a stable seasonal frost layer is deposited. This possibility is consistent with all of our data, and is additionally supported by the one early autumn image of a study site that we have that is clear enough for identification of at least one new 20 m-wide alcove (formed during L_S 169°–191°). (Again, we note that since we currently have only one clear example of formation during late summer–early autumn, we are not yet treating that formation timing as representative – but we are also not assuming that it was anomalous. The spatial correlation seen between other, less obvious, mass-wasting signs and dark features throughout the L_S 191° MY 32 Buzzel image also suggested that we may yet find more examples of early autumn-formed alcoves.) Within the latitude zone of Buzzel, seasonal frost formation is expected to begin at approximately L_S 170° (Kelly *et al.* 2006), so alcove formation within this time frame could be due to a seasonal frost-related process.

Where the alcoves form

Through all dune fields and Mars years, alcoves were observed only to form on the steeper, lee slopes of the dunes – which typically have slope angles of 15°–35° (Middlebrook 2015), the angle of repose (Atwood-Stone & McEwen 2013). In nearly all cases, slopes where alcove-formation activity occurred had sharp upper margins (i.e. the dune brink) and observable ripple migration, implying that these dunes experienced wind-driven sand fluxes and had at least a surficial layer of sand that was mobile. (The exception is Arakkis – discussed in the subsection on 'Some intriguing local-scale variations' later in this paper.) As these alcoves extended up to the dune brink, they cut back into the brink towards the upwind side of the dune, sometimes by several metres (Fig. 6).

Alcoves formed on all areas of these dune slip faces – in particular, on many of the barchan dune lee slopes, alcoves were seen to form on any part of the dune slip-face crescent (e.g. Fig. 3) and seemed independent of insolation direction, dune orientation, slope length or local brink curvature. Alcoves also could form in isolation/be 'dispersed' across a slope or form within 'clusters' (i.e. multiple new alcoves with spacing between the alcove 'centre points' of less than twice the average alcove widths – so touching or near to touching, at least along the dune brink) (Fig. 3). For example, during the winter of MY 29 at Palma dune field, numerous alcoves formed clusters along certain dunes. In some cases, the alcoves were so concentrated that they collectively cut into or 'backwasted' the brink along hundreds of metres of the slip face, making the dune brink appear to move backwards significantly.

The one noted control on new alcove activity was that no alcove was active beyond one Mars winter/spring season (i.e. no alcove was reactivated during a subsequent Mars year). Beyond that, there seemed to be little correlation in the locations of activity on a dune slope between Mars years – sometimes a new alcove formed next to an old alcove, and sometimes new alcoves formed far from the old alcoves (e.g. Fig. 3). (As it takes at least a few Mars years for the alcoves to disappear, as described in the following subsection, we currently lack the temporal baseline needed for determining when a restored dune slope may again experience alcove-formation activity.) This is a significant difference from the dune-gully activity seen in the southern mid-latitudes, where many of the features are active winter after winter (Diniega *et al.* 2010; Dundas *et al.* 2012, 2015).

Within a dune field and over a single Mars year, alcove activity was non-uniform in distribution (see Supplementary material for an example) and no clear trends with regards to latitude or dune size/type/distribution were apparent. In looking across multiple Mars years, we also investigated if alcove-formation activity was concentrated onto certain dunes within the field. In comparing between a few years within Kolhar and Buzzel, we found that many dunes were active only during 1 Mars year but some were active over multiple Mars years. Within these fields, we counted the number of alcove formations that occurred on the same dune slope, during more than 1 Mars year. Via a simple statistics analysis, we estimated the number of dunes that would be expected to undergo activity during multiple Mars years if the dune slopes that were active each year were randomly distributed. This comparison showed that in every Mars year combination, slightly to several more dunes experienced repeat activity than would be expected if alcove formation was completely independent between years (i.e. 1.1–5.4 standard deviations more than the expected number given a random distribution). While our estimation method is not yet sufficiently rigorous to be conclusive and we are working with small-number statistics, these results suggest that which dunes will undergo alcove formation during any Mars year may not be fully random. It is not yet clear if this could be due to some sort of physical feedback effect (although this seems less likely since the alcoves themselves are not reactivated) or to alcove-formation-conducive environmental conditions repeating in the same location between Mars years, yielding a 'clustering' of activity within our study sites (see the Supplementary material for further details on the statistical analyses and distributions).

Alcove–apron activity

As shown in Table 2, within most fields and most years, alcove activity was prolific, with 30–60% of the dunes containing at least one new alcove each Mars year. Inter-annual variations in activity may extend over the scale of the full polar region: through all sites examined in this study over more than 1 Mars year, alcove-forming activity was consistently higher in MY 29 and 31 (in the 'percentage of dunes active' and/or the 'number of alcoves'), relative to the activity observed in MY 30 and 32. However, as this inter-annual variation is most clearly seen in Kolhar, Buzzel and Palma (and especially in consideration of the MY 29 and 30 winters), the inter-annual variations may instead be regionally constrained –

observations of activity over additional Mars winters and sites are needed to more clearly establish the trends, and from that to identify likely processes or environmental controls for increases in alcove-formation activity rates.

Individual alcove volumes were commonly 0.5– 50 m^3, with most being of the order of 10 m^3 (i.e. 2–20 m^3) (Table 2). There were a few very large exceptions – in particular, most of the exceptionally large alcoves formed in Palma dune field during Mars winter MY 29 (see the subsection on ‘Some intriguing local-scale variations’ later in this paper) and a handful of very large alcoves formed within Buzzel during winter MY 31. As shown in Table 2, we have arbitrarily separated out alcoves with volumes exceeding 200 m^3, and do not consider them when we work with ‘representative’ alcove activity rates.

Minimum sand-flux amounts were estimated from the alcoves in Palma that formed during winter MY 29 and which disappeared (i.e. were filled in) by early MY 33. For these alcoves (generally the smaller ones that were comparable to those found in other dune fields), we estimated that 0.10–3.6 m^3 m^{-1} per Mars year of sand flux was needed to restore the dune slope and brink – with an average of 1.0 m^3 m^{-1} per Mars year. Similar effective aeolian sand-flux rates were also found for a few alcoves within Tleilax that filled in over the same time period. These rates are comparable to, although on the small side of, saltation-flux estimates within equatorial and north polar regions found via different estimation methods. For example, within Nili Patera, the migration rate of dunes and ripples was used to estimate an inter-dune flux of 2.3 m^3 m^{-1} a^{-1} or 4.3 m^3 m^{-1} per Mars year (Bridges *et al.* 2012). Within the north polar region, analysis of dune and ripple migration have yielded rates such as 2.5 m a^{-1} or 4.7 m per Mars year (Bridges *et al.* 2013) up to *c.* 7 m^3 m^{-1} per Mars year (Middlebrook 2015).

Discussion

Evaluation of formation mechanism hypotheses

To summarize: we found that alcoves form regularly and are active only through 1 Mars year’s seasonal cycle. An individual alcove forms some time during the autumn/winter season (i.e. between the last image taken in summer and the first image taken at the end of winter or the beginning of spring), and is in all but one case first observed frost-covered in the late winter or early spring. (For the exception, one rare early autumn image showed that at least one large alcove formed during the end of summer/beginning of autumn.) Through the spring season, as sublimation occurs, dark spots and dark flows (Gardin *et al.* 2010) are enhanced within the alcove. Dark spots and flows were nearly always found within the new alcoves, and sometimes clearly generated further slight mass-wasting activity (e.g. see Figs 2f, g & 8a, b for a few examples of sand avalanching down over the frosted surface). During the frost-free periods, sand ripples are actively migrating towards the dune brinks and delivering sand onto the slip faces, including alcoves. Within frost-free images, the alcove degrades in appearance over several Mars years as sand fills the depression and the dune slope is restored. While new alcove activity may happen near the existing alcove during subsequent Mars winters, and the alcove may be the site of sublimation activity (e.g. dark spots) during subsequent Mars winters, the alcove itself is not reactivated.

From the timing of alcove formation and enhancement activity, we find a clear seasonal control on the alcove activity (Table 3). Furthermore, we observe a two-phase process, with initial alcove activity generally constrained to the autumn/early winter time frame, followed by mass wasting due to springtime sublimation (Figs 1 & 2). Further work will aim to elucidate the specific mechanism and conditions under which the initial alcove formation occurs; but at this point, we at least rule out the hypothesis that alcove initiation may be season independent as no alcove activity is seen to occur during the summer (beyond infilling of old alcoves, which proves that the summer wind is strong enough to move sand). We most suspect a seasonal frost-related control, as winds are likely to be weakest during the summer (Forget *et al.* 1999; Richardson *et al.* 2007) and seasonal frost begins to condense and accumulate very soon after L_S 165° (including the period of L_S 169°–191°, when we identified at least one newly formed alcove: Fig. 5).

Some processes that could potentially play a role in destabilizing a dune slope during the autumn season are:

- Early, transient frosts that form and sublimate over a diurnal or day-to-week-scale weather change. Small-scale laboratory experiments run within Martian atmosphere and winter temperature conditions have shown that sublimation of small amounts of surface-condensed frost can initiate dry granular flows on slopes at and below the angle of repose (Sylvest *et al.* 2016). As discussed above, the seasonal frost layer begins to accumulate around L_S 170° within our higher latitude study sites, such as Buzzel dune field (Kelly *et al.* 2006).
- Early snowfalls that could pile snow on the dune slopes, before they are stabilized beneath the seasonal frost layer. Snowfalls are known to occur throughout the autumn and winter seasons within the polar regions (Hayne *et al.* 2012), including over the north polar regions containing these dune fields (Hayne *et al.* 2016). The earliest snowfalls may occur soon after L_S 180° within north polar sites, such as Tleilax dune field (Hayne *et al.* 2016).

Future work will aim to test some of these ideas – for example, if diurnal frosts play a role, then we may expect to see similar alcove-formation activity initiated at later times of the year within lower latitudes. Furthermore, we will continue to target HiRISE imaging during the late summer season so as to look for examples of early autumn alcove formation (although we expect this to work for only larger alcoves and only within a fortuitously less-hazy image). The results from such work will further constrain the model for alcove formation, yielding a more complete picture of the many ways in which seasonal frost and its processes affect the present-day Martian surface.

Relative importance of sand motion via frost or wind-driven processes for dune evolution

Using the approximate alcove sizes and a set of representative dune planform dimensions (taken from the Palma dune field, where the sand flux estimates were generated), we estimate the number of Mars years needed to move the representative dune's lee margin forward 1 m via each sand-transport mechanism. The method of estimating the volume of sand moved via alcove formation and aeolian sand flux was described above; we estimate the volume of sand that must move by assuming a lee-slope planform length of 40 m and a lee slope of *c.* 30°. For simplicity, we assume a transverse dune and thus neglect the geometrical effects of the barchan dune crescent. Focusing on 100 m of dune brink, 2300 m^3 of sand would need to be transported over the lee slope to move the lee margin forward by 1 m.

Over 100 m of dune brink, an effective aeolian sand flux of *c.* 1 m^3 m^{-1} per Mars year would yield 100 m^3 of sand moved per Mars year. Thus, it would take *c.* 23 Mars years to yield a full lee-slope movement of 1 m. We note that it would take only 7 Mars years if we assumed our maximum observed effective sand flux (3.6 m^3 m^{-1} per Mars year), but in our analysis we primarily focus on the average rate as we do not think the maximum estimated effective sand flux is representative of the sand flux that would be moving the full dunes. Instead, we think it likely that these rates reflect a local sand flux (see caveat 2, below), but emphasize that our maximum effective aeolian sand flux is sufficiently similar to our average value so as to not significantly alter our conclusions even if we did assume the higher value for the full field. We also again note that previous studies measuring dune and ripple motion within the north polar erg have had estimated higher rates of dune movement (e.g. up to 2.5 m a^{-1} or 4.7 m/Mars year by Bridges *et al.* 2013) or sand flux (*c.* 7 m^3 m^{-1} per Mars $year^{-1}$ by Middlebrook 2015) – but these values are still within the same order of magnitude as our average rate and, thus, assuming these higher rates would not greatly change our conclusion.

Alternatively, we consider conservative but representative rates of alcove activity: at an average new alcove volume of 7 m^3, 20% of the dune field experiences alcove formation each Mars year, and, on average, two alcoves form during an active year over 100 m of dune brink. These assumptions yield 3 m^3 of sand moving from upslope to downslope per year and 824 Mars years are needed to move the dune lee margin forward by 1 m, or *c.* 36 times longer than is needed with our average effective aeolian sand flux. Considering higher alcove activity rates that are still consistent with observations within some fields: at an average alcove volume of 15 m^3, 40% of the dune field experiences alcove formation each Mars year, and, on average, four alcoves form during an active year over 100 m of dune brink – then 24 m^3 of sand will move from upslope to down-slope per year and 96 Mars years are needed to move the dune lee margin forward by 1 m, or *c.* 4 times longer than the time needed within our average effective flux.

We acknowledge that there are many caveats to these estimations or comparisons between them. In addition to estimation techniques and assumptions described above, we note that:

1. Alcove-formation activity rates vary significantly between dunes, fields and Mars regions – as shown in Table 2. Our analysis above considers ‘representative’ and average rates, but unless rates are considered only over a very long temporal baseline and/or averaged over a very large area, inter-annual and inter-dune variation would probably need to be considered.

2. Our effective aeolian sand-flux estimate based on alcove in-filling is loosely constrained and may not be reflective of the actual amount of sand captured by the full dune slip face, and thus we may be incorrect in our expected timescale for aeolian sand-flux-driven dune migration. Additionally, aeolian sand fluxes

vary through the dune field (e.g. Lancaster 1985; Bridges *et al.* 2012) and region (e.g. Chojnacki *et al.* 2016). Aeolian sand fluxes also vary over an individual dune, with higher rates along higher portions of the dune brink (e.g. Walker & Nickling 2003; Bridges *et al.* 2012) or lowered rates in a particular direction due to the dune slope's curvature (e.g. Howard 1977). So while an observed alcove-infilling rate may reflect the sand flux occurring over that portion of the dune's brink, dune migration will result from the integration of the sand flux over the full dune brink.

3. Although both processes are acting on the downwind side of the dune, we do not know if the impacts of alcove formation and aeolian sand transport are purely additive. For example, sand could be loosened by alcove formation and then be blown back up to fill in the alcove – in an extreme end member, the net sand motion could be zero in this scenario and the dune could remain fixed.

However, given other observations of consistent dune margin shifts and many observations of bed-form migration within these fields (e.g. Bridges *et al.* 2013; Banks *et al.* 2015), it seems likely that these processes are both actively migrating and evolving the polar dunes. Our measurements yield a first estimation of the relative influence of alcove formation and aeolian sand flux on Martian polar dune evolution.

With our rough estimations, we find that that seasonally forming alcoves may account for 2–20% of the sand movement within our studied polar dunes. If alcove formation is a significant process acting on these dunes and contributing towards sand movement, this perhaps could account for a portion of the difference between our estimation of effective aeolian sediment flux (from alcove infilling) and in other estimations of sand flux (and sand displacement) rates. The aforementioned dune migration studies that included polar locations were measuring the total sand movement over several Mars years, and thus measured the net impact of both alcove formation and wind-driven sand transport. (Additional differences would come from the different methods used to estimate the actual sand flux, from proxy measurements such as ripple/dune migration or alcove infilling.)

Thus, while aeolian dune-building and alcove-formation rates and processes have been examined separately within past studies of these dune fields, we recommend that they be considered together within future interpretations of polar dune morphology and evolution.

A comment on the interior of polar dunes

As discussed above, and as shown in Table 2, many of these alcoves backwaste the dune brink extensively, releasing a very large amount of sand into a new apron on the lee slope that appears to be composed of unconsolidated sand. For example, Figure 6 shows a large alcove that backwasted the brink by nearly *c.* 10 m. That these large amounts of loose material are able to move downslope calls into question the idea that the core of the dunes may be frozen or otherwise cemented beneath a superficial mobile layer, unless the mobile layer is quite deep. It is possible that the alcove-formation process could be sufficiently energetic to break into a more cohesive core, but we see no clear sign of higher levels of cohesion within any alcoves, including the deepest one – such as steeper slopes or layering.

That north polar dunes may generally be composed of a deep layer of loose sand (that may extend through the full dune form) is also supported by the amount of sand motion seen via observations of ripple and dune margin shifts (e.g. Bridges *et al.* 2013; Banks *et al.* 2015). This sand motion generally seems to evolve the dune rather than expose indurated surfaces.

However, these dune fields also contain feature characteristics which have been thought to be evidence of significant intergranular cohesion, such as the very elongated, rounded barchan dunes found in Buzzel (this shape has been modelled as indurated dunes interacting with loose sand: Schatz *et al.* 2006) or thermal inertia measurements (which appear to be most consistent with a *c.* 30 cm-deep layer of basaltic sand over ground ice: Putzig *et al.* 2013). Future studies will need to reconcile the full suite of observations and measurements, including the alcove-formation activity and sizes, that can serve as proxy observations of the present state of the north polar dune interiors. Such studies will be likely to also look towards the many morphological differences between the apparently active north polar dunes and the likely arrested south polar dunes (Fenton & Hayward 2010; Banks *et al.* 2016) and the few similar north polar fields, like Arrakis (see the following subsection).

Some intriguing local-scale variations

We describe briefly here three fields with ‘unusual’ alcove-formation activity rates (at least when compared with the other fields studied here). We point these out as intriguing potential end members for the activity and controlling environmental conditions and processes, although work towards a full understanding of why these fields are different is beyond the scope of the current study and is the subject of ongoing work.

First, we were surprised at Arrakis’ lack of alcove formation. We examined this field in detail only via comparison of frost-free images in MY 29 and 30, but a cursory examination of this field within frost-free images taken during other Mars years yielded a consistent lack of changes, which was at odds with all other fields studied. Longer baseline comparisons (MY 29–33) also did not show substantial changes, ripple migrations or slip-face displacements. Nothing stood out with respect to Arrakis’ general geological context as being very different from the other studied dune fields. However, Arrakis’ dunes had a significantly different morphology to most in the north polar erg – with rounded tops/brinks, slopes that appear shallow and more diffuse margins. This appearance is reminiscent of sand dunes within the high southern latitudes, which do not appear to be mobile (i.e. no ripple or dune movement: Banks *et al.* 2016) and are hypothesized to be stabilized, possibly by ground ice (Fenton & Hayward 2010).

Second, very large alcoves formed within the Buzzel and Palma dune fields, especially during MY 29 (Table 2). Both the Buzzel and Palma dune fields contain dunes of comparative volumes and planform dimensions (Fig. 4), although Palma dunes have much longer slip faces than most other fields (which is likely to be due to having greater dune heights and empty interdune areas, such that the slip face can extend over a much larger portion of the lee slope/region of the dune). Additionally, some of these large features in Palma also had an alcove–channel–apron (ACA) appearance (similar to the dune gullies active in the southern mid-latitudes) v. the typical alcove–apron (AA) form of most of the features within the north polar dunes (including all of the large alcove features in Buzzel).

As we have not yet found a clear control other than alcove size regarding when the channels appear and when they didn't (and the size 'division' between ACA and AA features is gradual, and is different for different winters), we suspect that all alcove features in Palma form via the same general process(es). This strengthens our point that identifying the processes forming these north polar features will provide information relevant to understanding the processes driving evolution and modification of Martian dune gullies. Future work aims to explore the genetic connections between dune gullies with channels and alcove–apron features.

Third, the Chusuk dune field had only very small alcoves forming, although very many of them. The dunes within this field were very small compared to those found in other fields (Fig. 4) and, perhaps, the dune size exerted the main control in geometrically limiting the size of the alcoves.

Summary/conclusion

By examining alcove-formation activity through multiple dune fields and over multiple Mars years, we have identified clear trends and correlations that allow us to be as certain as is possible about when and how this activity occurs, and resolving the disagreement presented in past studies of this phenomena. Our observations have clearly shown that there is a seasonal control on the alcove activity, and that alcoves form through a two-phase process. The first phase, which generates the initial alcove formation, is constrained to the autumn/early winter time frame and precedes deposition of part, if not all, of the stable seasonal frost layer. The second phase of activity is primarily further mass wasting within these new alcoves due to springtime sublimation. After the frost disappears, then infilling of old alcoves occurs due to wind-blown sand and mass wasting of the lee slope, and these alcoves are not observed to reactivate in later Mars winters.

By examining the full life cycle of the alcoves, we have estimated the sand-transport rate due to both alcove formation and the aeolian sand flux – thus generating a first estimation of the relative influence of alcove formation and aeolian sand flux on Martian polar dune evolution. We find that seasonally forming alcoves may account for 2–20% of the sand movement within our studied polar dunes, and postulate that, perhaps, this could partially account for why high sand flux and sand displacement rates have been found in studies of dune and ripple movement within the north polar erg, v. within equatorial dune fields. We have estimated sand-flux rates completely separate from alcove-formation-driven sand transport by looking at alcove infilling rates, while other studies of sand transport are likely to have measured the net impact of both alcove formation and wind-driven sand transport.

The main conclusion of this work is that both aeolian sand transport and alcove-formation processes are significantly modifying the dunes within the Martian north polar erg, and thus that both wind-driven and seasonal-frost-driven processes should be considered together within future interpretations of polar dune morphology and evolution. With this study, we have begun to put numbers to those rates, and to further constrain the exact mechanism by which alcoves are forming. Future work that aims to also understand the anomalous activity rates and alcove sizes, as well as the discrepancy seen between the extensive surface activity and possible cemented dune cores, will help to elucidate the intriguing interplay between seasonal frost and wind processes in this area of Mars and yield insights into how these two forces are sculpting the present-day Martian surface.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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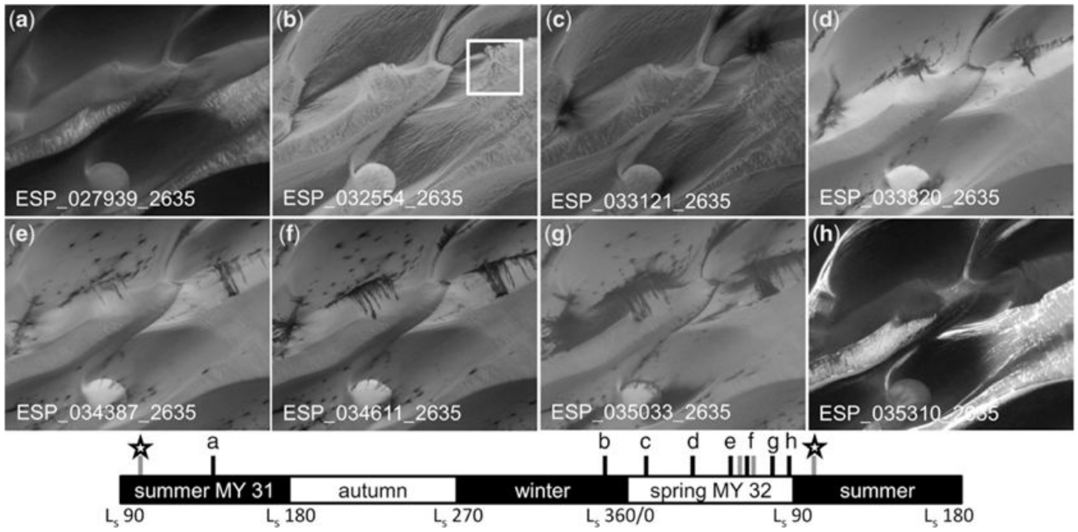

Fig. 1.

Example of the formation of alcove–aprons within Tleilax dune field (83.5° N, 118.5° E). Shown are a representative sampling of the HiRISE images (NASA/JPL/UA) available for tracking of changes – four additional images are indicated in the timeline with the grey bars and are shown in the Supplementary material, including the images used for initial identification of changes, starred in the timeline but not shown here. Note the large time period between (**a**) & (**b**) images due to the lack of HiRISE images taken during the polar hood and polar winter (dark) conditions – which coincides with when the alcove–apron feature first formed. Defrosting activity (dark spots, fans and flows) occurs through the spring (**c**)–(**g**) and seems to enhance the alcove–apron. After the frost is removed from the feature (**h**), no further alcove–apron formation or enhancement activity occurs; instead, the alcoves may become less apparent through summer, as the dune slope becomes restored (probably through aeolian sand transport into the alcoves). The box in the second image shows the location of the zoom-in shown in Figure 2. A scale bar is not shown as images are not orthorectified (and some are taken with the emission angle greater than a few degrees, generating foreshortening effects) – but the full area shown is approximately 700 × 550 m. In this and all HiRISE images, north is up and illumination is from the right; defrosted images have been stretched in brightness to bring out details on the dark (and sometimes shadowed) lee slope.

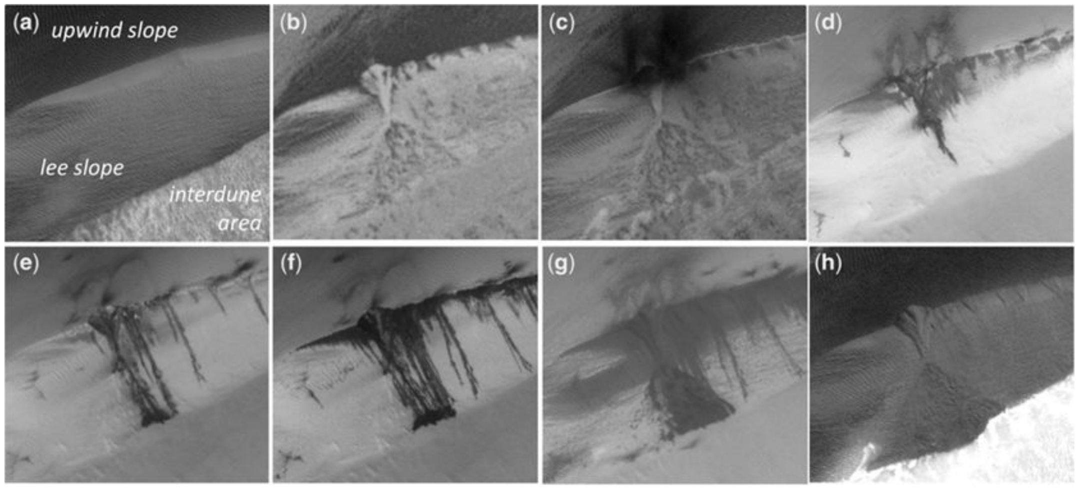

Fig. 2.

Zoom-in of one large alcove–apron formation example within the box-location shown in Figure 1. As denoted in the first image (**a**), the upper 'line' transitioning from dark to lighter dune material is the dune brink, and the lower 'line' transitioning to yet brighter material is the terminal margin of the lee dune slope (i.e. the boundary between the dune lee slope and the interdune substrate). A scale bar is not shown as images are not orthorectified and some are taken from higher spacecraft slew angles – but the area shown is approximately 200 × 180 m. Note that to the right of the main alcove examined here, many other smaller alcoves formed along the dune brink – again, first visible in image (**b**) due to both topography visible under the frost and deviations within the dune brink shape. These alcoves were also focused sites of defrosting processes in images (**c**)–(**g**), and then were still visible after defrosting had completed in image (**h**). The Supplementary material contains four more images.

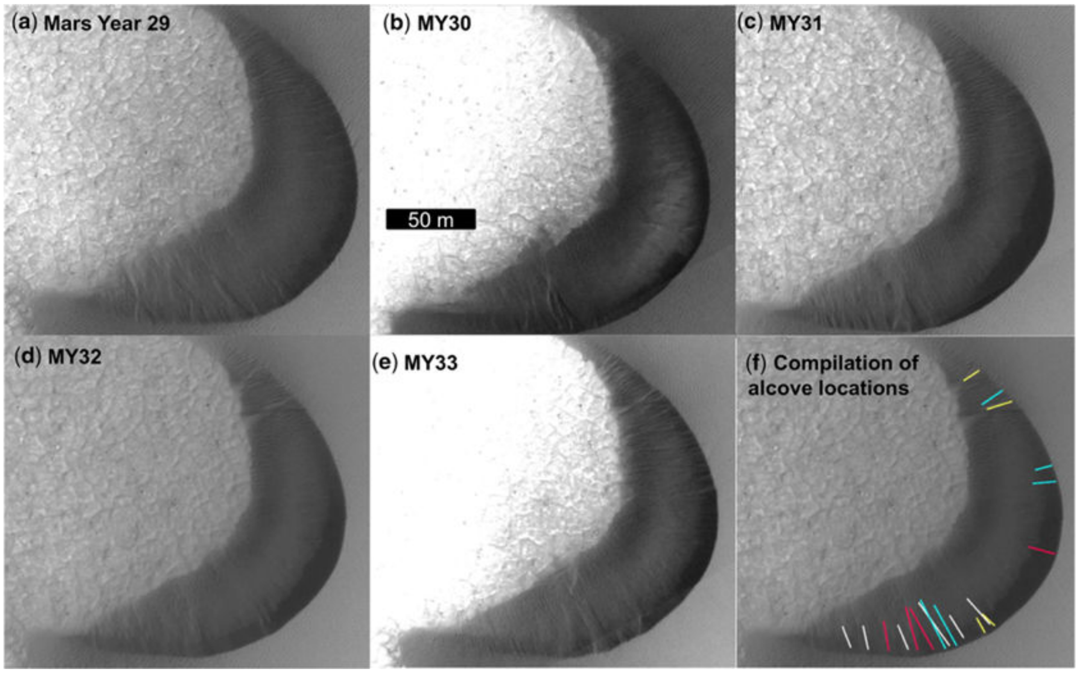

Fig. 3.

Appearance and erasure of alcove–apron features on a small barchan in Palma dune field (76.2° N, 95.4° E). These images are all from the defrosted seasons, and were chosen because (**b**)–(**e**) were taken with emission angles <1° and thus foreshortening effects are minimized; (**a**) was the earliest clear image of this dune. HiRISE images used are: (a) PSP_009743_2565, L_S 117° MY 29; (b) ESP_018011_2565, L_S 98° MY 30; (c) ESP_027914_2565, L_S 137° MY 31; (d) ESP_036630_2565, L_S 134° MY 32; (e) ESP_044806_2565, L_S 110° MY 33 (NASA/JPL/UA). Within (**f**), the long axis of all alcoves are marked (over the same image shown in d). White indicates that the alcoves were present in (a); red alcoves appeared during winter MY 29, none appeared during winter MY 30, yellow appeared in during winter MY 31 and blue appeared during MY 32. Although not explicitly marked, note also the disappearance of alcoves over the years as the dune slope and brink is restored through aeolian sand transport.

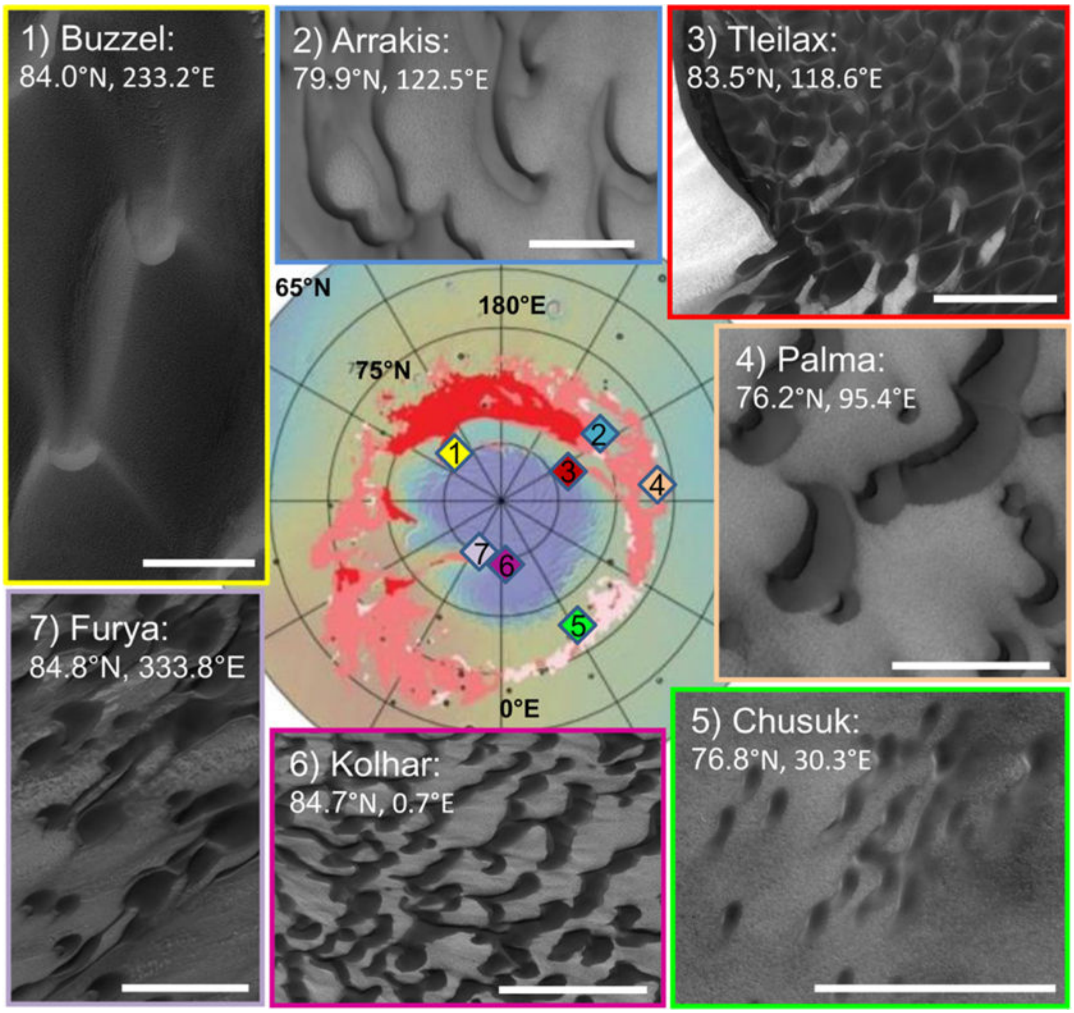

Fig. 4.

Map showing the location of all study sites, and representative snapshots of each field, ordered by longitude. Within each image, the bar shown is 100 m. Images used for the fields are Buzzel: ESP_036387_2640, L_S 124° MY 32; Arrakis: ESP_018867_2600, L_S 113° MY 30; Tleilax: ESP_026950_2635, L_S 102° MY 31; Palma: ESP_018525_2565, L_S 116° MY 30; Chusuk: ESP_027758_2570, L_S 131° MY 31; Kolhar: ESP_027521_2650, L_S 122° MY 31; Furya: ESP_018963_2650, L_S 132° MY 30 (NASA/JPL/UA). The background map image shows the dune field (reds and pinks) distribution within the north polar erg (Hayward *et al.* 2010); the NPLD can be found along the edges of the north polar cap (the purple and blue feature in the middle – the base colour scheme indicates elevation).

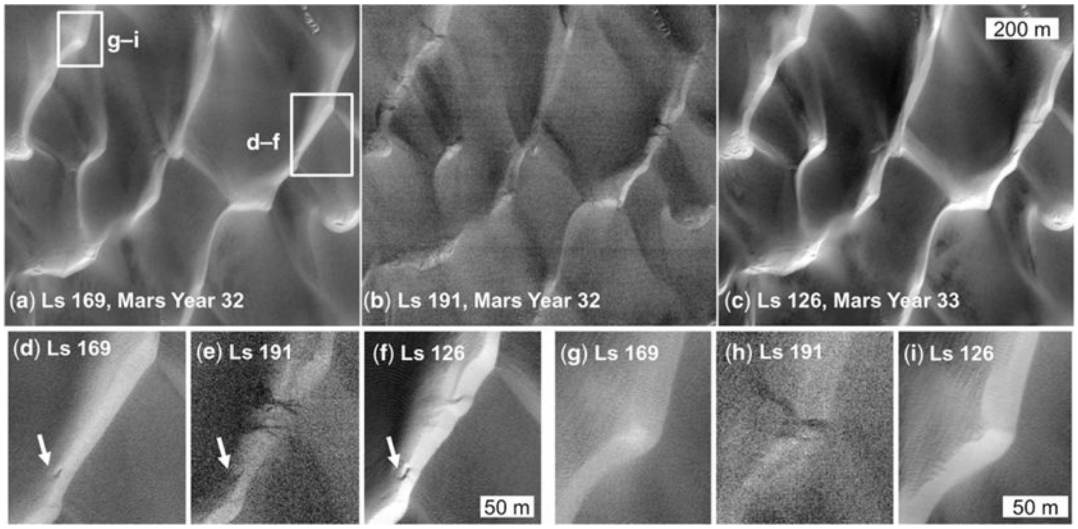

Fig. 5.

A portion of the one HiRISE image taken during early autumn of one of our study sites that is sufficiently clear to look for, and identify, new alcove formation. This autumnal image of the Buzzel dune field (**b**) was taken at L_S 191° MY 32, *c.* 1.5 Earth months after the preceding, end of summer, image (**a**) was taken at L_S 169°. In (b) dark features (some of them triangular and similar in appearance to alcoves) extend down the lee slopes from the dune brinks. The locations of many of these dark features correlate with new alcoves or other slope changes (such as changes in margin shape or texture/ripple patterns) identified within (**c**, L_S 126° MY 33) after comparison with an image taken *c.* 1 Mars year before (ESP_036387_2640: L_S 124° MY 32, not shown), and with image (a). Two such features are highlighted within image sequences (**d**)–(**f**) and (**g**)–(**i**), within zoom-ins from (a)–(c). Smaller slope features, such as hummocky terrain at the base of the downwind slope, are visible in all images (one example is indicated with an arrow in d–f), which indicates that the observed changes are not just a function of different lighting conditions. Throughout this field, most of the examples of possible mass-wasting features first visible within image (b), such as that shown in (g)–(i), do not satisfy our requirements of correlation with a new alcove identified within the next year's defrosted image and a clear dune brink change; we highlight (d)–(f) as this new alcove is one example that can be clearly identified within image (b). HiRISE images shown: (a), (d) & (g) ESP_037521_2640; (b), (e) & (h) ESP_038035_2640; and (c), (f) & (i) ESP_045262_2640 (NASA/JPL/UA).

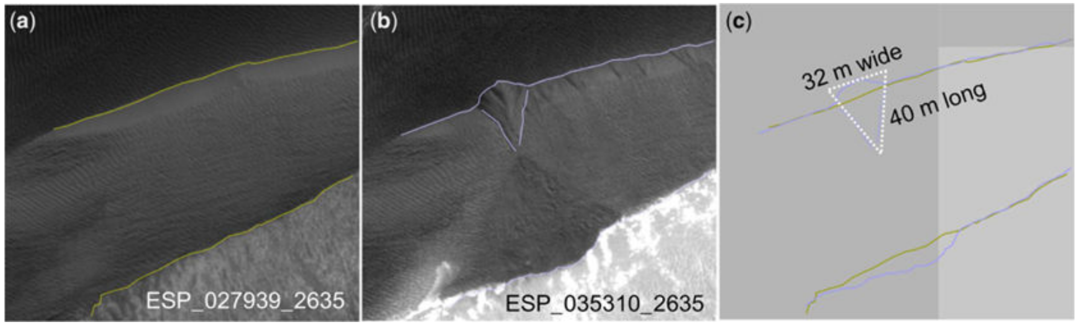

Fig. 6.

Example of alcove volume estimation, using the example shown in Figure 2. From planform dimensions of the alcove width/length taken from ESP_035310_2635 (a near-nadir HiRISE image: emission angle of 0.6°) and assuming an average depth of 0.3 m (i.e. 1/100 of the width), we estimate that 200 m^3 of sand was displaced in the formation of the alcove. In this case, this conservative volume estimate may be too low – at its maximum, the brink backwasted nearly 10 m.

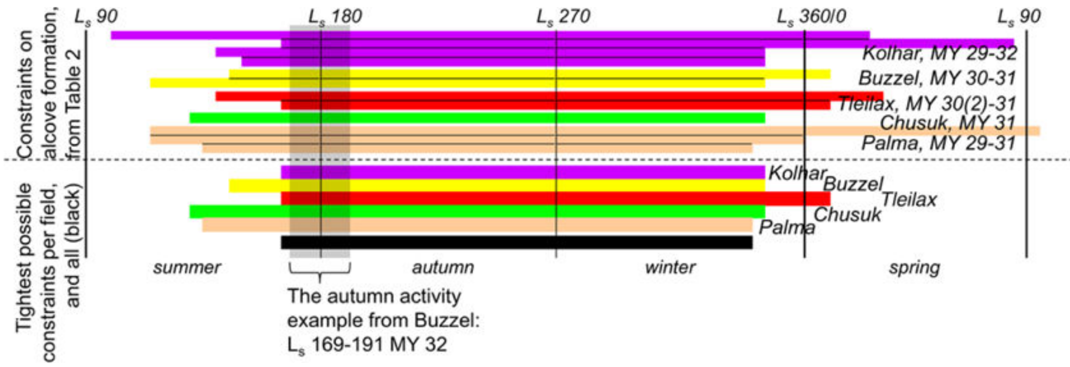

Fig. 7.

Plot of the timing constraints for when alcove–apron formation occurred within Kolhar (pink), Buzzel (yellow), Tleilax (red), Chusuk (green) and Palma (tan) (the colour scheme is the same as in Fig. 4; exact timing constraints are listed in Table 2) as determined within our study site surveys. Within the upper portion, the different Mars years are shown (except for Tleilax MY 30 – the bars are for two regions of the study site, as the images did not overlap fully). These periods, within which we know the alcoves formed, generally are bracketed by the last image taken during summer and the first image taken as the Sun peeks over the pole again after winter night, so the timing of alcove-formation activity cannot be constrained tighter but we can eliminate all other times (when many more images were taken). The lower portion shows the tightest possible timing constraints for activity within each field (i.e. if we could assume no significant inter-annual variations in the timing of activity), and the bottom-most black bar shows the tightest possible timing constraints for activity for all fields (i.e. if we could also assume no significant variations with latitude or proximity to the pole) based on existing observations. While we should not assume a lack of regional or inter-annual variations in the timing of activity, the lack of alcove-formation activity outside of these bars does suggest strongly that activity is not related to a frost-free process. This is strengthened by the one example we have found (so far) for tightly constrained activity timing: as shown in Figure 5, at least one large alcove has been confidently matched with activity that occurred between L_S 169° and L_S 191° during MY 32 in the Buzzel dune field (shown in the superimposed shaded region).

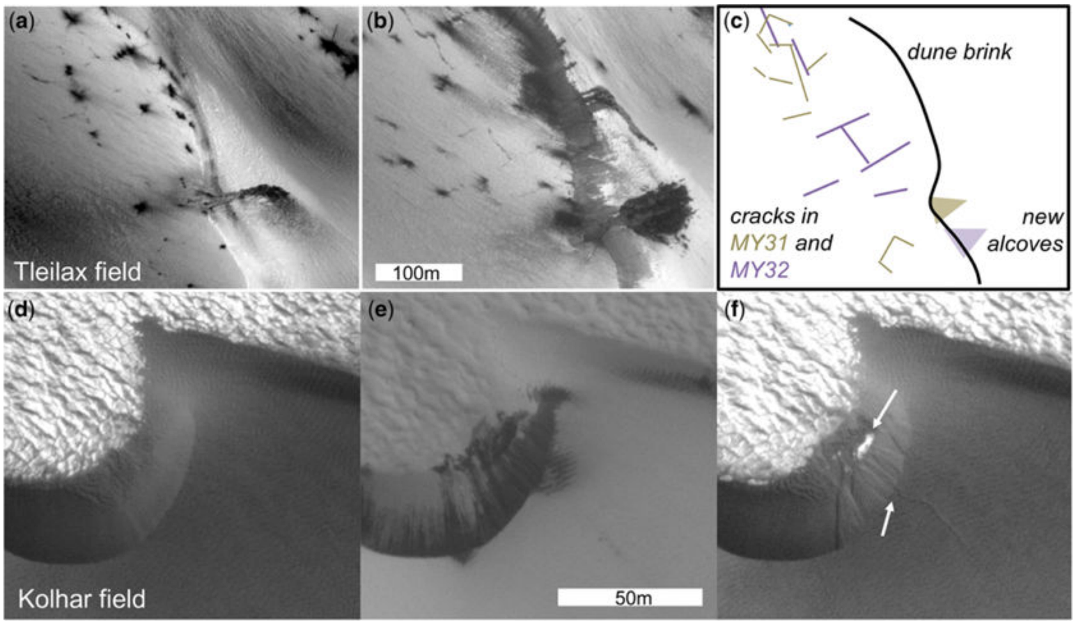

Fig. 8.

An example of features seen throughout the north polar dunes, which we interpret as evidence that the seasonal frost layer sinters into an icy layer over these dunes. (**a**)–(**c**) show cracks in the seasonal frost layer that formed over the Tleilax dune field, during two Mars springs. These cracks become visible at *c.* L_S 20° and remain visible/stable in appearance through *c.* L_S 80°, when the full surface becomes defrosted. The location of the dune brink and prominent new alcoves are also shown in (c) to orientate the viewer. (**d**)–(**f**) show the appearance of a furrow extending from the dune brink, down the upwind slope of the dune. (d) shows the previous year's defrosted image, (e) shows the sublimation activity occurring during the spring season and (f) shows that below the intersection of the new furrow and the brink (lower arrow within the image); an area of the dune lee apron appears to have been cleared of sediment (upper arrow), perhaps due to the energetic sublimation activity of a fallen ice block. The furrow extends towards the bottom right-hand corner of the image, about halfway to the corner from the dune brink. HiRISE images shown: (a) ESP_025381_2635, L_S 48° MY 31; (b) ESP_035033_2635, L_S 77° MY 32; (d) PSP_008968_2650, L_S 90° MY 29; (e) ESP_017460_2650, L_S 78° MY 30; (f) ESP_017895_2650, L_S 95° MY 30 (NASA/JPL/UA).

Table 1

Original hypotheses, motivating measurements that could help distinguish different controls/underlying processes for the alcove formation

Measurement	**→ Aeolian process (Horgan & Bell 2012)**	**→ Seasonal frost process (Hansen *et al.* 2011, 2015)**
Orientation of alcove long-axis, with respect to north		Possibly concentrated on pole-facing slopes
Location/orientation of the alcove on the dune	Will originate mostly on brink edges that are parallel to ripples found on the upwind slope (that is perpendicular to the local dominant wind direction), which is presumably the portion of the dune most strongly affected by the present-day dominant wind	Will be concentrated on more 'sheltered' slopes where frost accumulation may be enhanced
When the alcove would form	Year-round or at least not associated with only frosted periods; possibly only during defrosted periods as the stable seasonal frost layer could armour the dune surface, decoupling it from the wind	When frost is present
Repeat activity or later enhancement within an existing alcove	Unlikely to occur (near-) annually on the same slope (unless restoration processes can quickly fill in the alcove and 'over-steepen' the slope – this should be observable)	Frost accumulation is enhanced within topographical lows, so (near-) annual repeat activity may be expected (again, unless restorative processes can fill-in the alcove that quickly – observable)
Resultant displacement direction of the dune brink	The brink of the dune advances evenly forward	The brink of the dune would 'wiggle' in position as alcoves backwaste the brink towards the upwind slope and then are filled in; may backwaste over a large brink length if several alcoves are clustered close enough to merge along the brink (and would the dune recover?)

Table 2

Alcove–apron formation rates, per field and per Mars year, sorted by latitude, for study sites where full survey and measurement have been completed

Dune field	Winter (MY)	Timing of activity (L_S)	No. of new alcoves	Alcove volume (m^3)	Average alcove volume (m^3)	% of dunes active
Furya: 84.8° N, 333.8° E	29	–	150	0.8–74	7	60
Kolhar: 84.7° N, 0.7° E	29	102–26	525	0.7–58	11	30
	30	166–83	62	0.6–36	5	5
	31	141–350	734	0.4–47	7	40
	32	152–351	111	0.5–73	8	8
Buzzel: 84.0° N, 233.2° E	30	144–11	57	0.6–55, +one large: 430	14; 7 excluding large	5
	31	118–348	97	0.4–58, +four large: 205, 287, 467, 650	23; 7 excluding large	8
Tleilax: 83.5° N, 118.6° E	30	139–34, 166–13 (the images did not fully overlap)	550	0.6–44	5	50
Arrakis: 79.9° N, 122.5° E	29	–	2	2	2	*c.* 0
Chusuk: 76.8° N, 30.3° E	31	131–348	>600	0.3–4	1	50
Palma: 76.2° N, 95.4° E	29	117–97	192	10–194 + 22 large: 201, 208, 212, 224, 245, 249, 271, 289, 302, 323, 337, 357, 391, 434, 492, 541, 556, 557, 726, 1153, 1387	117; 64 excluding large	50
	30	116–2	154	0.7–127	13	35
	31	137–343	158	0.7–34	7	40

If no L_S range is given for the 'timing of activity', too few images were available that year to constrain it to a season(s). The alcove volume is estimated from length and width (with depth approximated as1/100 of the width) – this is reported in place of the planform measurements as it provided the simplest estimate of 'alcove size'; the aspect ratio of the alcoves varied widely within all fields and across all years. 'Large' alcoves are arbitrarily defined as those with volumes >200 m^3

Table 3

Observation results, analysed against the hypotheses outlined in Table 1

Measurement	→ Aeolian process	→ Seasonal frost process
Orientation with respect to north	*No clear trend seen – Inconclusive*	
Location/orientation on the dune	*No clear trend seen – Inconclusive*	
When gullies/changes first become visible		Constrained to autumn/winter (and one feature constrained to early autumn)
Are gullies forming in same locations as old gullies/is activity modifying and extending existing features?	The location of steep slopes may partially control where gullies form – e.g. all alcoves are on steep, lee slopes and an alcove is not reactivated in a later year. However, this level of control is not seen within the southern mid-latitude dune gullies, which can reactivate over multiple Mars years. (and a longer temporal baseline is needed to see how long after slope restoration a new alcove may form)	Activity for a given alcove feature is constrained to a single, sequential autumn/winter/spring set. Observed spring activity is correlated with and appears to be driven by sublimation activity (e.g. dark spots, dark flows).
Displacement direction of the dune brink	Some consistent downwind margin movement has been observed in north polar dunes (not yet determined if it occurs in the specific dunes considered within this study). However, such studies also observe higher rates of sand movement than we find with our estimated effective aeolian sand flux – probably based on the differences in how these proxy measurements relate to actual sand flux (e.g. those based on dune migration would be based on the net result of both the alcove-formation process and wind-driven sand transport)	Examples of significant backwasting are found